ONR Graduate Traineeship Award in Ocean Acoustics for Sunwoong Lee

Prof. Nicholas C. Makris
Massachusetts Institute of Technology
77 Massachusetts Avenue, Room 5-212
Cambridge, MA 02139
phone: (617) 258-6104 fax: (617) 253-2350 email: makris@mit.edu

Sunwoong Lee
Massachusetts Institute of Technology
77 Massachusetts Avenue, Room 5-435
Cambridge, MA 02139
phone: (617) 253-1032 fax: (617) 253-2350 email: sunwoong@mit.edu

Grant Number: N000140510073

LONG-TERM GOALS

The long-term goal of this research is to develop optimal array signal processing techniques for source/target localization and identification in littoral shallow-water environments. It has long been known that multi-modal dispersion in a shallow water waveguide degrades the performance of bearing estimates by conventional plane-wave beamforming. This is due to spurious effects unique to the waveguide environment such as multiple peaks and beam spreading in the beamformer output [1, 2]. We plan to develop array signal processing techniques that account for and exploit multi-modal wave propagation and dispersion.

OBJECTIVES

The primary objectives of the research are to:

- develop optimal shallow-water source localization techniques that require little *a priori* knowledge of the wave propagation environment.
- analyze reverberation and target scattering in range-dependent shallow-water waveguides accounting for multi-modal wave propagation and scattering phenomena.
- develop shallow-water synthetic aperture sonar (SAS) techniques for towed line arrays to improve cross-range resolution.

APPROACH

The approach is to theoretically derive array signal processing techniques for optimal source/target localization in a dispersive waveguide, and to apply these techniques to experimental data. Data acquired from the Acoustic Clutter Experiments in 2001 and 2003 have been used to investigate the performance and accuracy of our techniques. The data have also be used to elucidate the scattering mechanisms of submerged targets and environmental reverberation in shallow-water waveguides.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE
ONR Graduate Traineeship Award in Ocean Acoustics for Sunwoong Lee

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Massachusetts Institute of Technology,77 Massachusetts Avenue, Room 5-212,Cambridge,MA,02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
The long-term goal of this research is to develop optimal array signal processing techniques for source/target localization and identification in littoral shallow-water environments. It has long been known that multi-modal dispersion in a shallow water waveguide degrades the performance of bearing estimates by conventional plane-wave beamforming. This is due to spurious effects unique to the waveguide environment such as multiple peaks and beam spreading in the beamformer output [1, 2]. We plan to develop array signal processing techniques that account for and exploit multi-modal wave propagation and dispersion.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

WORK COMPLETED

The research work in Fiscal Year 2005 was a great success in developing a new, innovative *array invariant* source localization techniques in a dispersive waveguide that require little *a priori* knowledge of the environment. The array invariant techniques enable instantaneous source-range estimation in a horizontally-stratified ocean waveguide from passive beam-time intensity data obtained after conventional plane-wave beamforming of acoustic array measurements.

The method has significant advantages over existing source localization methods such as matched field processing or the waveguide invariant. First, no knowledge of the environment is required except that the received field should not be dominated by purely waterborne propagation. Second, range can be estimated in real time with little computational effort beyond plane-wave beamforming. Third, array gain is fully exploited. The method has been applied to data from the Main Acoustic Clutter Experiment of 2003 for source ranges between 1 to 8 km, where it is shown that simple, accurate, and computationally efficient source range estimates can be made.

RESULTS

Attempts have been made to localize sources submerged in ocean waveguides by exploiting multi-modal interference using methods such as matched field processing (MFP) [3, 4, 5]. Apart from being computationally expensive, MFP techniques require accurate knowledge of the wave propagation environment. They are susceptible to large systematic errors from mismatch when adequate environmental information is not available [6, 7].

The range of a source in a horizontally stratified ocean waveguide can sometimes also be estimated by the much simpler waveguide invariant method [8, 9, 10], which employs only incoherent processing of acoustic intensity data as a function of range and bandwidth. The waveguide invariant method, however, requires knowledge of certain "invariant" parameters, which unfortunately often vary significantly with ocean sound speed structure. It also requires a sufficiently large number of waveguide modes to significantly contribute to the measured field because these cause the interference structure necessary to produce a unique solution. Sufficiently dense sampling of the intensity data in source-receiver range is also necessary to provide an unambiguous solution. When the application involves single-sensor measurements, joint ambiguity in source-receiver range and velocity is an inherent limitation of the waveguide invariant method. This ambiguity can disappear when spatial sensor arrays of sufficient horizontal aperture are used. None of the usual benefits of increased signal-to-noise ratio at the array output appear, however, because only incoherent processing of the spatial samples can be performed.

We have shown that instantaneous source range estimation is possible in a horizontally stratified ocean waveguide by a computationally inexpensive method that has significant advantages over the waveguide invariant because it requires neither *a priori* knowledge of environmental parameters nor multiple modes in the received field, and fully exploits the coherent gain possible with receivers of finite spatial aperture [11]. Since the new approach takes advantage of invariant properties of passive beam-time intensity data obtained after conventional plane-wave beamforming of underwater acoustic array measurements, we call it the *array invariant* method. We have shown that maximum beam-time intensity migrates along an angle that is invariant to environmental parameters but follows a known and unique dependence on source-receiver range. Horizontal source localization is also achieved when

the receiving array has sufficient horizontal aperture to resolve source bearing. The array invariant method is applicable for both broadband transient source signatures [11] and continuous broadband random noise signatures [12].

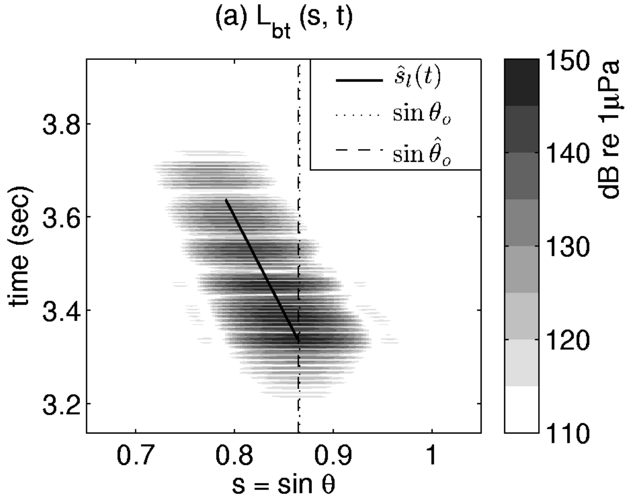

Figure 1: Beam-time image $L_{bt}(s, t)$ as a function of array scan angle $s = \sin\theta$ and time t, with true source range r_o = 5 km and bearing θ_o = 60° in the Pekeris sand waveguide. The dotted and dashed vertical lines are at $\sin\theta_o$ and $\sin\hat{\theta}_o$, respectively, where $\hat{\theta}_o$ is the scan angle of the array corresponding to the global maximum of the $L_{bt}(s, t)$ data. The black solid line is the linear least squares fit $\hat{s}_l(t)$ of peak intensity angle versus time.

An example of beamformed pressured field received by a horizontal line array after standard time domain beamforming is shown in Fig. 1, where migration of the beamformed field in array scan angle and time domain can be observed. This migration due to waveguide dispersion can be shown to be independent of the environmental parameters, but depends only on the source location in a known, unique way. This property enables instantaneous range estimation of a source in an ocean waveguide with no *a priori* knowledge of the environment.

We have demonstrated the performance of the array invariant method at range estimation with field data acquired during the Main Acoustic Clutter Experiment (MAE) of 2003 conducted in the New Jersey Strataform area [13, 14]. Water depth typically varied from 70 to 80 m, and source range from 1 to 8 km for the data considered. The measured beam-time sound pressure level data $L_{bt}(s, t)$, obtained after time-domain beamforming and matched filtering of the acoustic field received on the horizontal array for one of the source transmissions is imaged in Fig. 2 (a). The range and bearing of the source with respect to receiver coordinates are r_o = 3.6 km and θ_o = -65° by GPS measurement. The linear least squares fit of the beam-time migration line $\hat{s}_l(t)$ is overlain on Fig. 2 (a). The slope of the fitted line is the array invariant estimate, $\hat{\chi}_l = 0.339$. The source range r_o is then estimated as $\hat{r}_o = -c(z)\sin\hat{\theta}_o / \hat{\chi}_l = 4.1$ km. This is within 14% of the true range, which is sufficient for many practical applications. A corresponding simulation is in Fig. 2 (b), which shows an excellent agreement with the measurement in Fig. 2 (a).

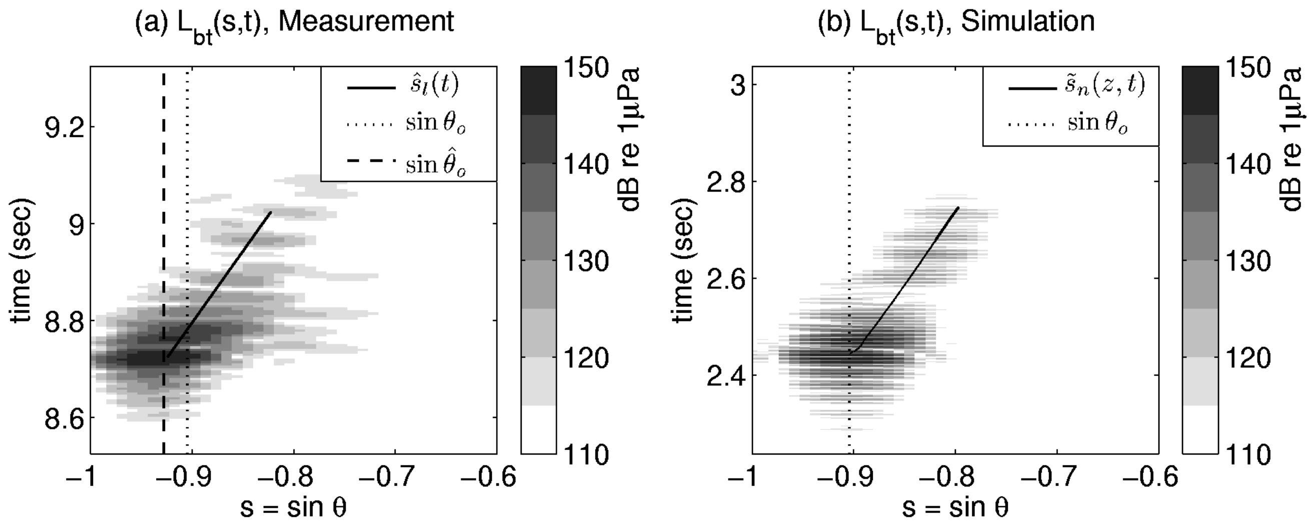

Figure 2 : (a): The beam-time sound pressure level image $L_{bt}(s, t)$ measured during the MAE 2003. The dotted vertical line is at $\sin\theta_o$, and the dashed vertical line is at $\sin\hat{\theta}_o$, where θ_o = -65° and $\hat{\theta}_o$ = -68°. The slanted line is the linear least squares fit of peak beam-time migration. The receiver depth is 39.7 m. (b): Simulation of the measurement shown in Fig. 2 (a). The positions of $\sin\theta_o$ and $\sin\hat{\theta}_o$ are nearly identical.

We have shown that source range can be consistently and robustly estimated using the array invariant method with experimental field data. Source range was estimated 241 times for ranges between 1 to 8 km over the period of 6 hours using MAE data. High correlation was found between source range estimates using the array invariant method and ranges measured by GPS. The range estimates $\hat{r}_o$ using the array invariant method are shown in Fig. 3 along with the GPS measured ranges r_o for tracks 141a_1, 141d_1, 84_1, and 85_4. Figure 4 shows range estimates $\hat{r}_o$ versus GPS measured ranges r_o for all four tracks. The solid line in Fig. 4 is the linear regression of $\hat{r}_o$ with respect to r_o. The regression coefficient and the correlation coefficient of 0.946 and 0.835, respectively, are high and indicate that the data have significantly supported the array invariant range estimation model. The root mean square (RMS) error of all range estimates determined by the array invariant method is 25% of the source range. The accuracy of this particular experimental configuration shows that the array invariant is of extreme practical value.

Even greater accuracy can be achieved for similar measurement scenarios if the source is omnidirectional. The vertical linear source array used in this experiment significantly degraded performance by suppressing higher order modes, especially at long ranges. This is not typical of mobile sources that are detected and tracked in operational systems. The length of the receiver array used in the MAE was roughly 64 λ / 2, half the length of many standard arrays. Using a more typical 128 λ / 2 aperture array would increase the range resolution by a factor of 2, since the range resolution of the array invariant method is roughly proportional to receiving array beamwidth.

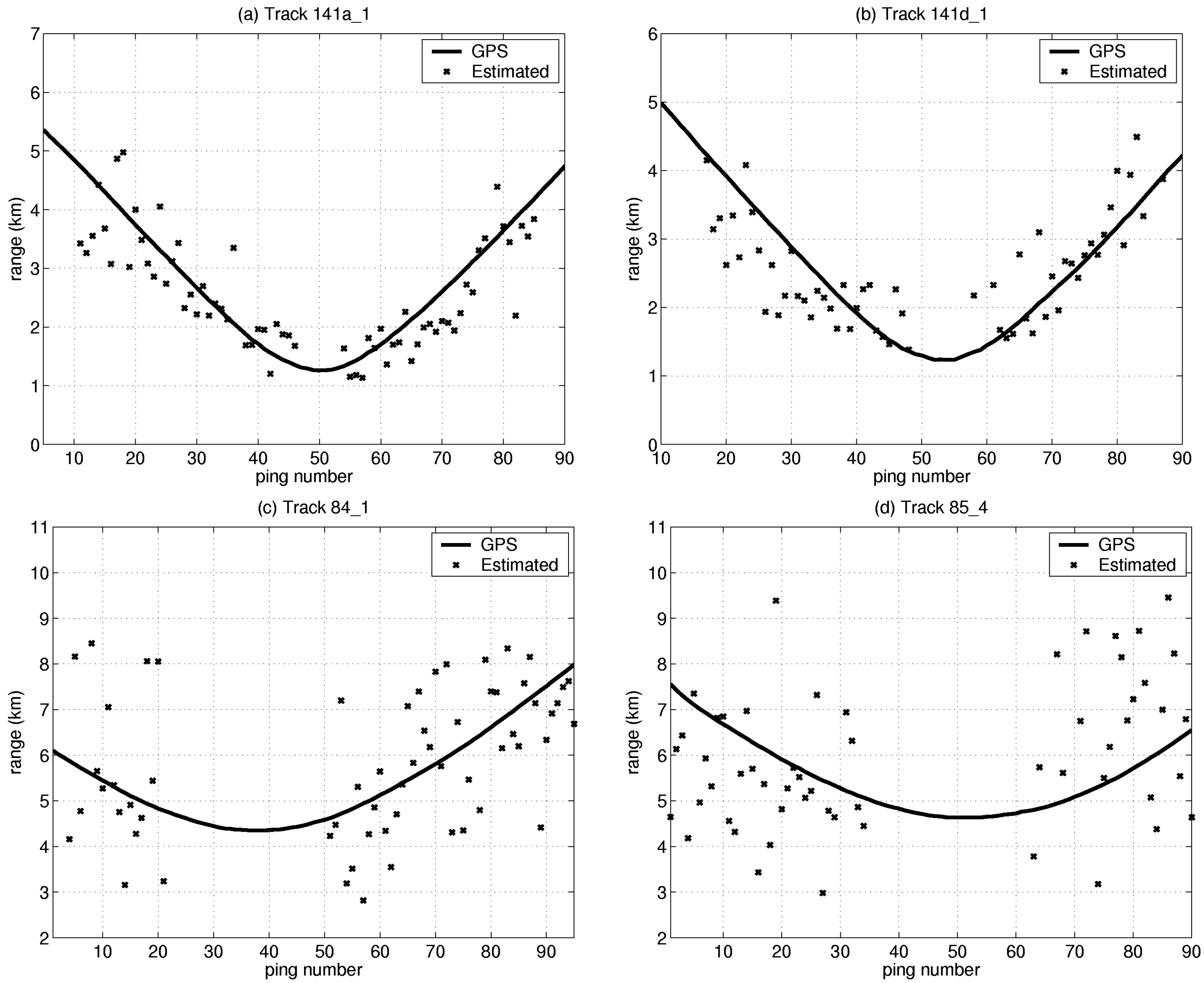

Figure 3: Experimental range estimates using the array invariant method. The solid lines show r_o measured by GPS. The cross marks show $\hat{r}_o$ estimated by the array invariant method. (a) Track 141a_1: 66 range estimates are shown, and 3 noise-corrupted data are ignored. The RMS error e_{rms} is 0.6 km. (b) Track 141d_1: 58 range estimates are shown, and 4 noise-corrupted data is ignored. The RMS error e_{rms} is 0.6 km. (c) Track 84_1: 61 range estimates are shown, and 8 noise-corrupted data are ignored. The RMS error e_{rms} is 1.4 km. (d) Track 85_4: 56 range estimates are shown, and 6 noise-corrupted data are ignored. The RMS error e_{rms} is 1.7 km.

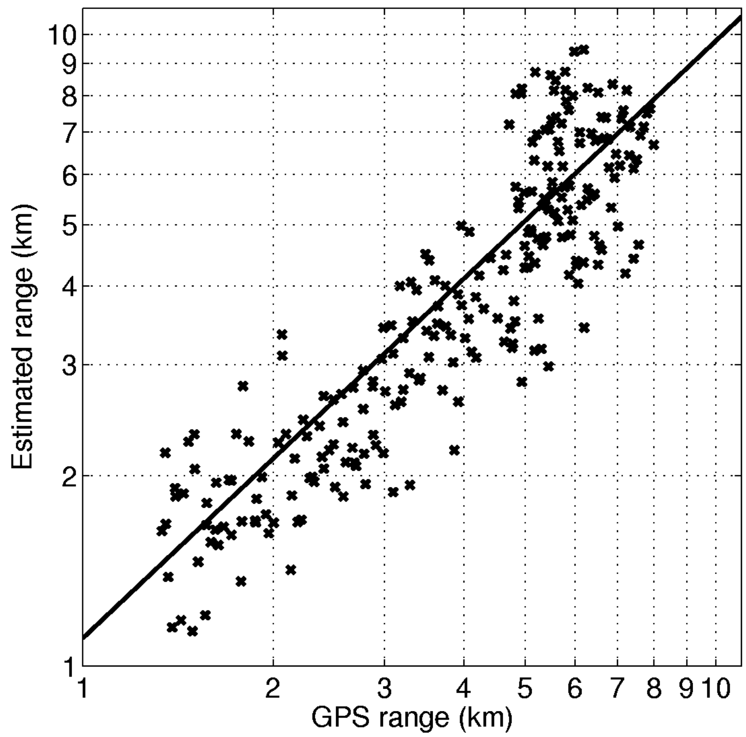

Figure 4: Experimental range estimates using the array invariant method. The range estimates $\hat{r}_o$ versus GPS measured ranges r_o for tracks 141a_1, 141d_1, 84_1, and 85_4 plotted in logarithmic scale. The solid line is the linear regression $\hat{r}_o = a + b\ r_o$, where the regression coefficient b = 0.946 and the intercept a = 161 m. The correlation coefficient is 0.835.

IMPACT/APPLICATIONS

The array invariant method developed from Fiscal Year 2005 effort has significant advantages over existing source localization methods for practical source localization scenarios. This is because the array invariant method does not require *a priori* knowledge of the environmental parameters, nor does it require extensive computations. The ability to make simple and accurate range estimates by the array invariant method has been demonstrated with data from the Main Acoustic Clutter Experiment of 2003.

The array invariant method has tremendous potential application in shallow-water surveillance missions and anti-submarine warfare. The method will enable instantaneous and simultaneous localization of noise sources in a littoral environment using towed arrays from surface ships or submarines.

REFERENCES

[1] C. S. Clay. Array steering in a layered waveguide. *J. Acoust. Soc. Am.*, 33(7):865-870, 1961.

[2] N. C. Makris and P. Ratilal. A unified model for reverberation and submerged object scattering in a stratified ocean waveguide. *J. Acoust. Soc. Am.*, 109(3):909-941, 2001.

[3] H. P. Bucker. Use of calculated sound fields and matched field detection to locate sound sources in shallow water. *J. Acoust. Soc. Am.*, 59:368-373, 1976.

[4] A. B. Baggeroer, W. A. Kuperman, and H. Schmidt. Matched field processing: Source localization in correlated noise as an optimum parameter estimation problem. *J. Acoust. Soc. Am.*, 83(2):571-587, 1988.

[5] H. Schmidt, A. B. Baggeroer, W. A. Kuperman, and E. K. Sheer. Environmentally tolerant beamforming for high-resolution matched field processing: Deterministic mismatch. *J. Acoust. Soc. Am.*, 88(4):1851-1862, October 1990.

[6] C. Feuillade, D. R. DelBalzo, and Mary M. Rowe. Environmental mismatch in shallow-water matched-field processing: Geoacoustic parameter variability. *J. Acoust. Soc. Am.*, 85(6):2354-2364, June 1989.

[7] G. B. Smith, H. A. Chandler, and C. Feuillade. Performance stability of high-resolution matched-field processors to sound-speed mismatch in a shallow-water environment. *J. Acoust. Soc. Am.*, 93(5):2617-2626, 1993.

[8] S. D. Chuprov. Interference structure of a sound field in a layered ocean.. In L. M. Brekhovskikh and I. B. Andreevoi, editors, *Acoustics of the Ocean: Current Status* (*in Russian*), pages 71-91. Nauka, Moscow, 1982.

[9] L. M. Brekhovskikh and Y. Lysanov. *Fundamentals of Ocean Acoustics*. Springer-Verlag, New York, 3rd edition, 2003.

[10] G. L. D'Spain and W. A. Kuperman. Application of waveguide invariants to analysis of spectrograms from shallow water environments that vary in range and azimuth. *J. Acoust. Soc. Am.*, 106(5):2454-2468, November 1999.

[11] S. Lee and N. C. Makris. A new invariant method for instantaneous source range estimation in an ocean waveguide from passive beam-time intensity data. *J. Acoust. Soc. Am.*, 116(4):2646, 2004.

[12] S. Lee and N. C. Makris. Range estimation of broadband noise sources in an ocean waveguide using the array invariant. *J. Acoust. Soc. Am.*, 117(4):2577, 2005.

[13] N. C. Makris. *Main Acoustic Clutter Experiment Cruise Report*. Technical report, Office of Naval Research, 2003.

[14] P. Ratilal, Y.-s. Lai, D. T. Symonds, L. A. Ruhlmann, J. A. Goff, C. W. Holland, J. R. Preston, E. K. Scheer, M. T. Garr, and N. C. Makris. Long range acoustic imaging of the continental shelf environment: The Acoustic Clutter Reconnaisance Experiment 2001. *J. Acoust. Soc. Am.*, 117(4):1977-1998, 2005.

PUBLICATIONS

- S. Lee, N. C. Makris, The array invariant, *J. Acoust. Soc. Am.*, In press, 2005.

- N. C. Makris, S. Lee, A new invariant method for instantaneous source range estimation in an ocean waveguide from passive beam-time intensity data, *Proceedings of 1st International Conference on Underwater Acoustic Measurements: Technologies and Results*, 1233-1236, 2005.

- S. Lee, N. C. Makris, Range estimation of broadband noise sources in an ocean waveguide using the array invariant, *J. Acoust. Soc. Am*. 117, 2577, 2005.

- P. Ratilal, S. Lee, Y. Lai, T. Chen, D. Symonds, N. Donabed, N. C. Makris, Range-dependent 3D scattering and reverberation in the continental shelf environment from biology, geology and oceanography, *J. Acoust. Soc. Am.* 117, 2611, 2005.

- S. Lee, N. C. Makris, A new invariant method for instantaneous source range estimation in an ocean waveguide from passive beam-time intensity data, *J. Acoust. Soc. Am.* 116, 2646, 2004.

- S. Lee, P. Ratilal, N. C. Makris, Explaining extended linear features observed in remote sonar images of the New Jersey continental shelf break during Acoustic Clutter Experiments in 2001 and 2003, *J. Acoustic. Soc. Am*. 115, 2618, 2004.